CS 3700
Networks and Distributed Systems

Lecture 14: Time + Logical Clocks

(Based off slides by Rik Sarkar at University of Edinburgh)

Global time

- In practice, we act like there is a global notion of time

  e.g., What time is it?

- But, time is relative
  - Einstein showed speed of light constant for all observers
  - Leads to *Relativity of Simultaneity*

- Basically, impossible to tell if two events are simultaneous
  - If events are separated by space
  - *But*, if events are causally connected, can preserve order

Global time in systems

- For human-scale systems, these differences don't matter
  - Rarely are we going near the speed of light

- But these do come to play in computing systems
  - Must consider relativity of time when designing systems
  - E.g., high-frequency trading systems
    - Need to be able to declare who bought first
  - Or, need to be able to merge multiple writes to single object

Outline

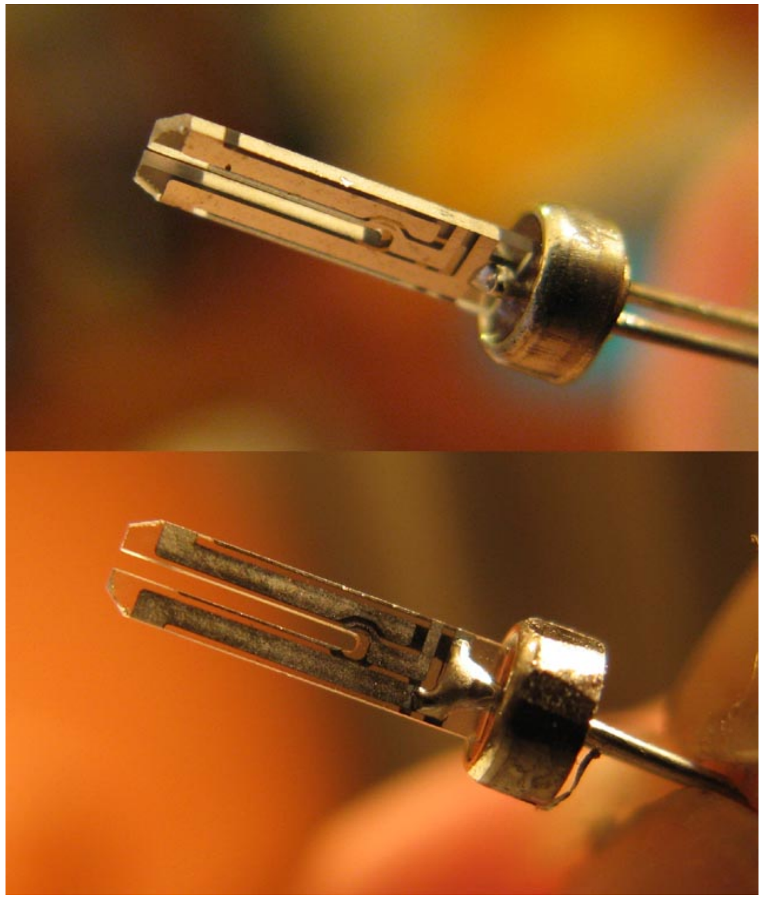
- Defining and measuring time
- Correcting clocks
- NTP
- Logical clocks
- Vector clocks

Historic clocks

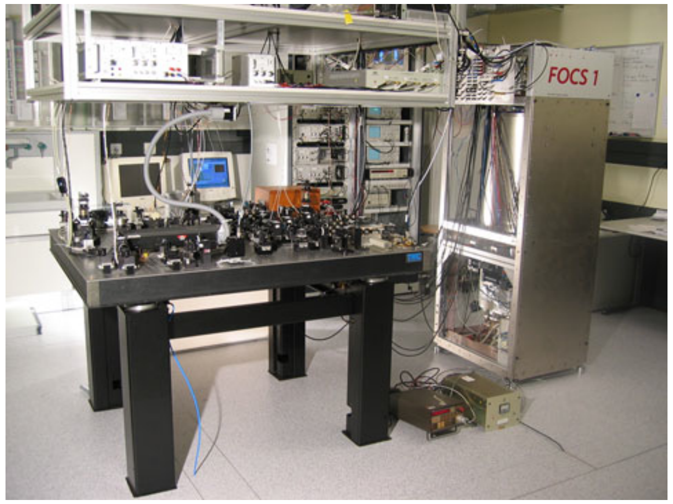
- Our units of time date from the Sumerians in 2000BC
  - Sexagesimal system based on hand counting
- Humans used a variety of devices to measure time
  - Sundials
  - Astronomical clocks
  - Candle clocks
  - Hourglasses
- Mechanical clocks developed in medieval ages
  - Typically maintained by monks (church bell tower)

Electronic clocks

- First developed in 1920s
  - Uses carefully shaped quartz crystal
  - Pass current, counts oscillations
- Most oscillate at 32,768/sec
  - Easy to count in hardware
  - Small enough to fit (~4mm)
- Typical quartz clock quite accurate
  - Within 15 sec/30 days (6e-6)
  - Can achieve 1e-7 accuracy in controlled lab conditions
  - Not good enough for today's applications



Atomic clocks



- Based on atomic physics
  - Cool atoms to near absolute zero
  - Bombard them with microwaves
  - Count transitions between energy levels
- Most accurate timekeeping devices today
  - Accurate to within 10^{-9} seconds per day
  - E.g., loses 1 second in 30 million years
- SI second now defined in terms of atomic oscillations
  - 9,192,631,770 transitions of cesium-133 atom

TAI

- Atomic clocks used to define a number of time standards
- **TAI**: International Atomic Time
  - Avg. of 200 atomic clocks, corrected for time dilation
- Essentially, a count of the number of seconds passed

Measuring real-world time

- Originally, each town defined noon locally
  - Point at which sun highest in the sky
- With growth of railroads, this became impractical
  - Continually have to re-set watches
  - Hard to set rail schedules
- Notion of "time zones" developed
  - Regions where wall-clock time is the same
  - Now, need to synchronize clocks

GMT, UT1, and UTC

- **GMT:** Greenwich Mean Time
  - Originally, mean solar time at 0° longitude
  - This isn't really "noon" due to Earth's axial tilt
- **UT1:** Universal Time
  - Modernized version of GMT
  - Based on rotation of Earth, ~86,400 seconds/day
- **UTC:** Universal Coordinated Time
  - UT1 + leap seconds
  - Minutes can have 59-61 seconds
  - Since 1972, 25 leap seconds have been introduced

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Correctness

- What does it mean for a clock to be correct?
  - Relative to an "ideal" clock
  - *Clock skew* is magnitude, *clock drift* is difference in rates
- Say clock is correct within *p* if

$$(1-p)(t'-t) \leq H(t') - H(t) \leq (1+p)(t'-t)$$

  - $(t'-t)$ True length of interval
  - $H(t') - H(t)$ Measured length of interval
  - $(1-p)(t'-t)$ Smallest acceptable measurement
  - $(1+p)(t'-t)$ Largest acceptable measurement
- Monotonic property: $t < t' \Rightarrow H(t) < H(t')$

Monotonicity

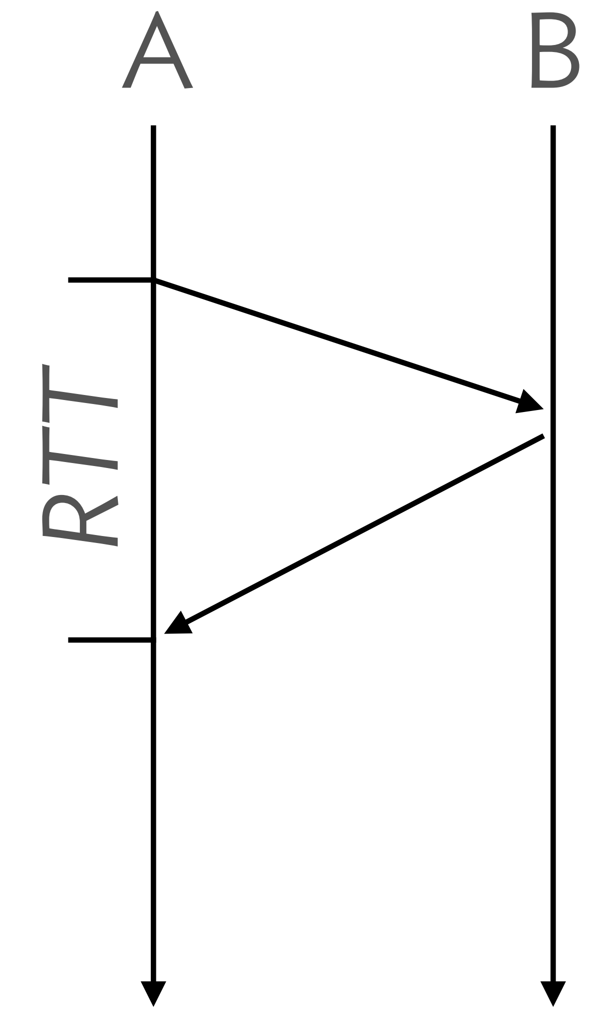
- If a clock is running "slow" relative to real time
  - Can simply re-set the clock to real time
  - Doesn't break monotonicity
- But, if a clock is running "fast", what to do?
  - Re-setting the clock back breaks monotonicity
  - Imagine programming with the same time occurring twice
- Instead, "slow down" clock
  - Maintains monotonicity

Simple synchronization

- If we know message delay T
  - A sends current time t to B, who sets time to $t+T$
- Typically, don't know exact delay
  - May know range on delay $min < T < max$
  - B can then set time to $t+(max-min)/2$
  - Clocks are then within $(max-min)/2$ of each other
- Can general this protocol to many clocks
  - Overall accuracy still $\sim(max-min)$
- But, don't generally have any bound on delay

Cristian's method

- No assumption of delay bound
- *A* sends request to *B* of current time
  - *B* responds with local time *T*
  - *A* measures RTT
  - *A* sets local time to *T+RTT/2*
- Assumes that delay is symmetric
  - Why?
- *A* can do this many times in a row, use overall min *RTT*
- Rough accuracy is *RTT/2 - min*, with overall min *min*



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Synchronizing in the real world

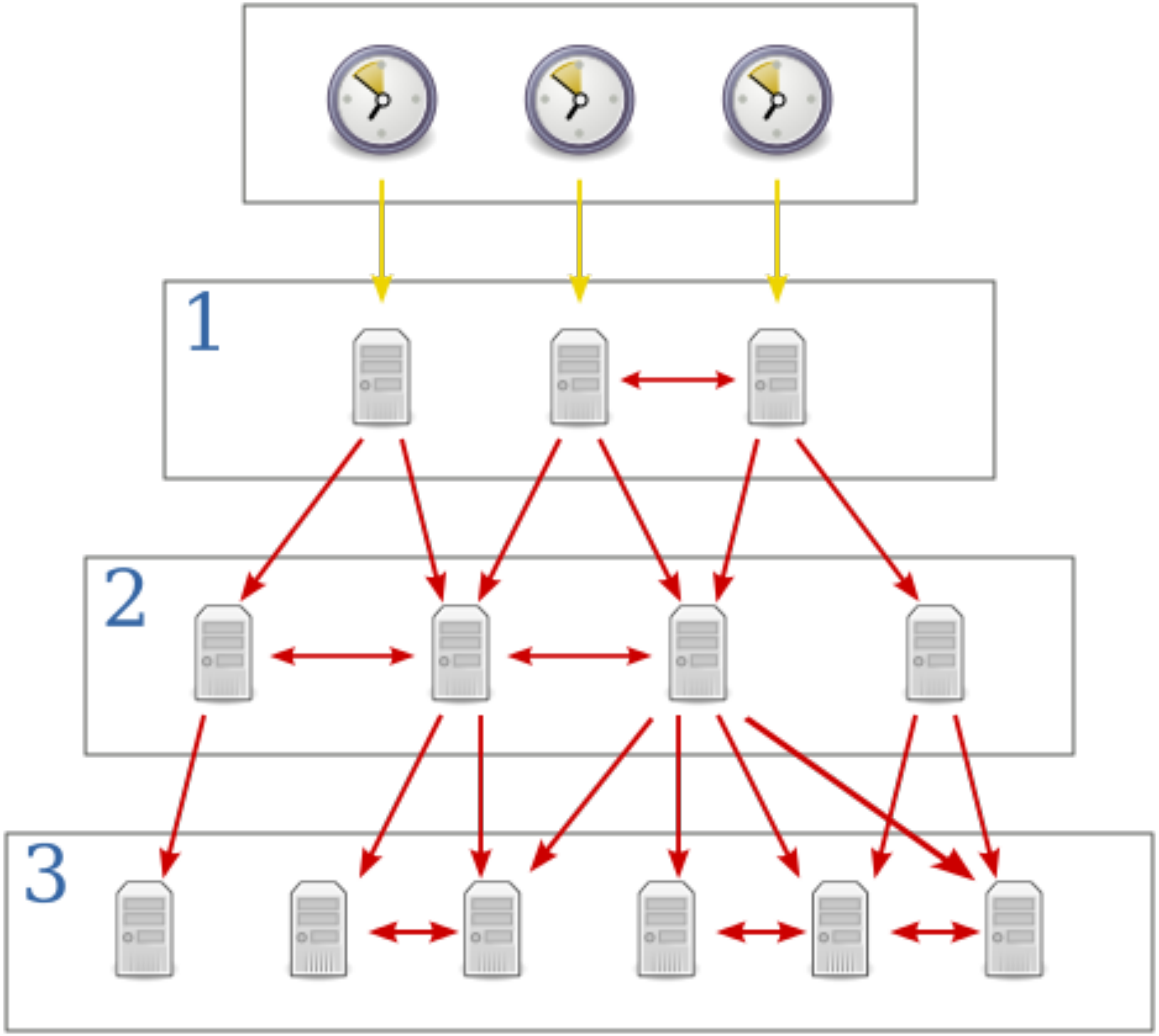
- *Network Time Protocol* (NTP) developed in 80s with goals
  - Keep machines synchronized to UTC
  - Deal with lengthly losses of connectivity
  - Enable clients to synchronized frequently (scalable)
  - Avoid security attacks

- NTP deployed widely today
  - Uses 64-bit value, epoch is 1/1/1900 (rollover in 2036)
  - LANs: Precision to 1ms
  - Internet: Precision to 10s of ms

NTP Hierarchy

- Based on hierarchy of accuracy, called *strata*
  - **Stratum 0:** High-precision atomic clocks
  - **Stratum 1:** Hosts directly connected to atomic clocks
  - **Stratum 2:** Hosts that run NTP with stratum 1 hosts
  - **Stratum 3:** Hosts that run NTP with stratum 2 hosts
  - …
- Stratum *x* hosts often synch with other stratum *x* hosts
  - Provides redundancy

NTP strata



NTP in practice

- Run on UDP port 123
- Most Internet hosts support NTP
- Accuracy on general Intenet is ~10ms
  - Up to 1ms on local networks, ideal conditions
- Many networks run local NTP servers
  - E.g., `time.ccs.neu.edu`
- NTP has recently been a vector for DDoS attacks
  - Best practice is for servers to filter requests outside local network

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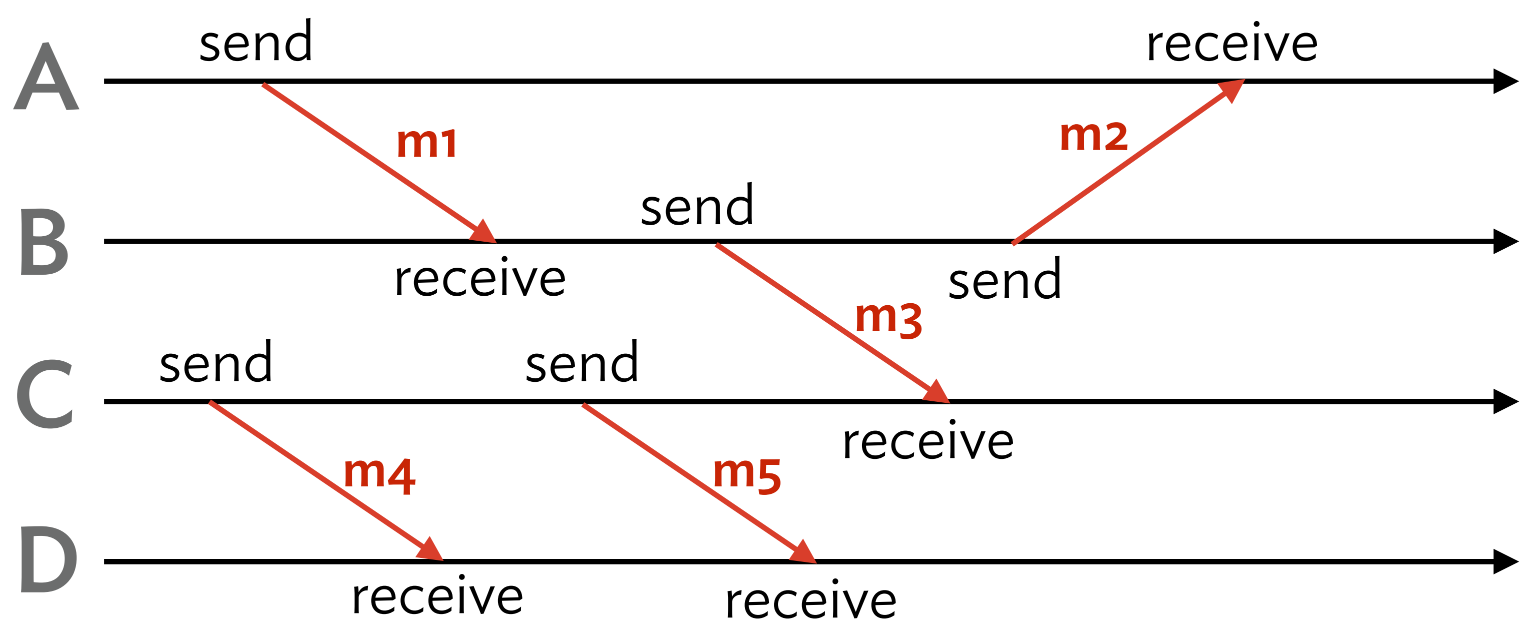
Logical ordering

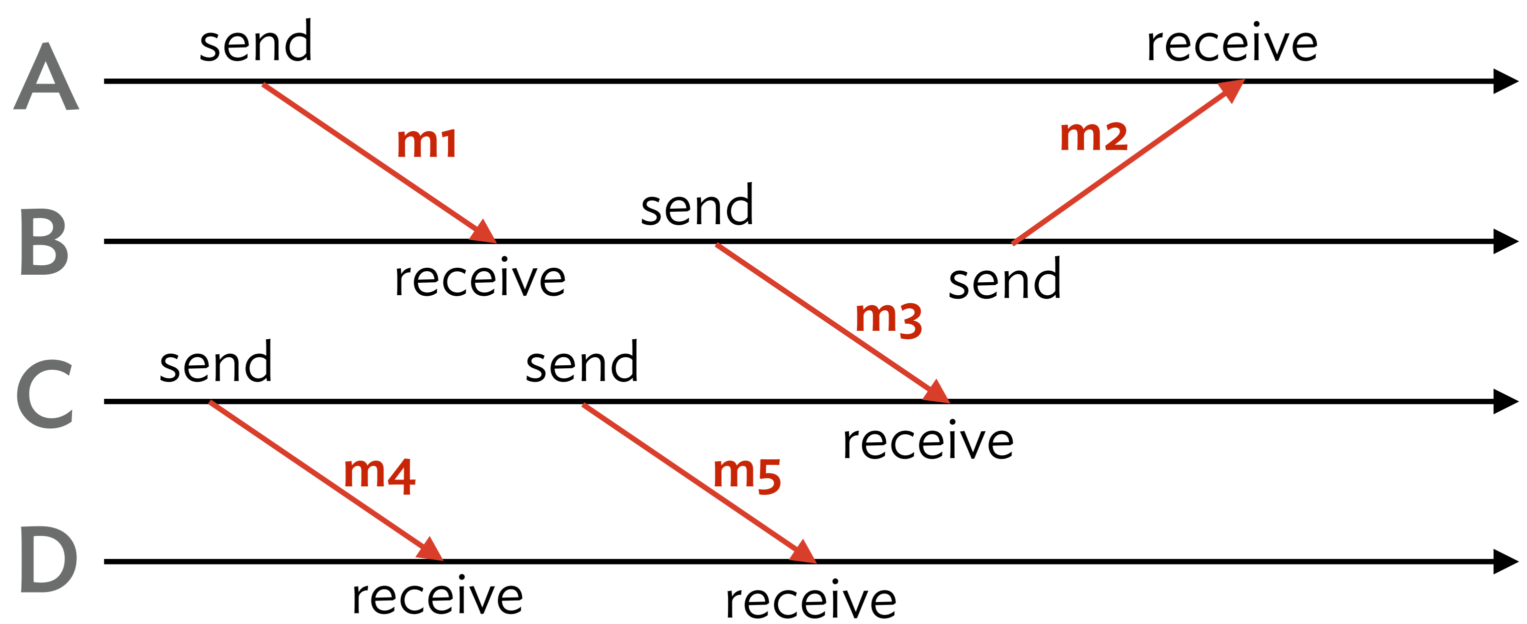
- Goal: Be able to provide some synchronization of events
  - Recall, never able to do perfectly synchronize clocks
- How to deal with this fact in the real world?
- Create a new abstraction: *Logical ordering*
  - Remove real-world time from equation
  - Base ordering on causality
- Logical clocks are based on the simple principles:
  - 1. Events observed by a single process are ordered
  - 2. Any message must be sent before it is received

Example of logical ordering



- Each host can order all events it observes
  - *B* observes m1 received before m3 sent
- Can "interleave" timelines via messages
- Cannot make statement about all pairs of events
  - E.g., m5 send and m1 receive can't be ordered

Happened-before relation



- Formalize logical clocks via *happened-before* (→) relation
  - If *e1* precedes *e2* on single host, then *e1* → *e2*
  - If *e1* and *e2* and send/receive of message, then *e1* → *e2*
  - *e1* → *e2* and *e2* → *e3*, then *e1* → *e3*
- If neither *e1* → *e2* nor *e2* → *e1*, then *e1* and *e2* are concurrent
  - Say *e1* || *e2*

Limits of happened-before

- Cannot capture external events
  - Only considers message-passing; phone call?
  - Two events may be concurrent in our system

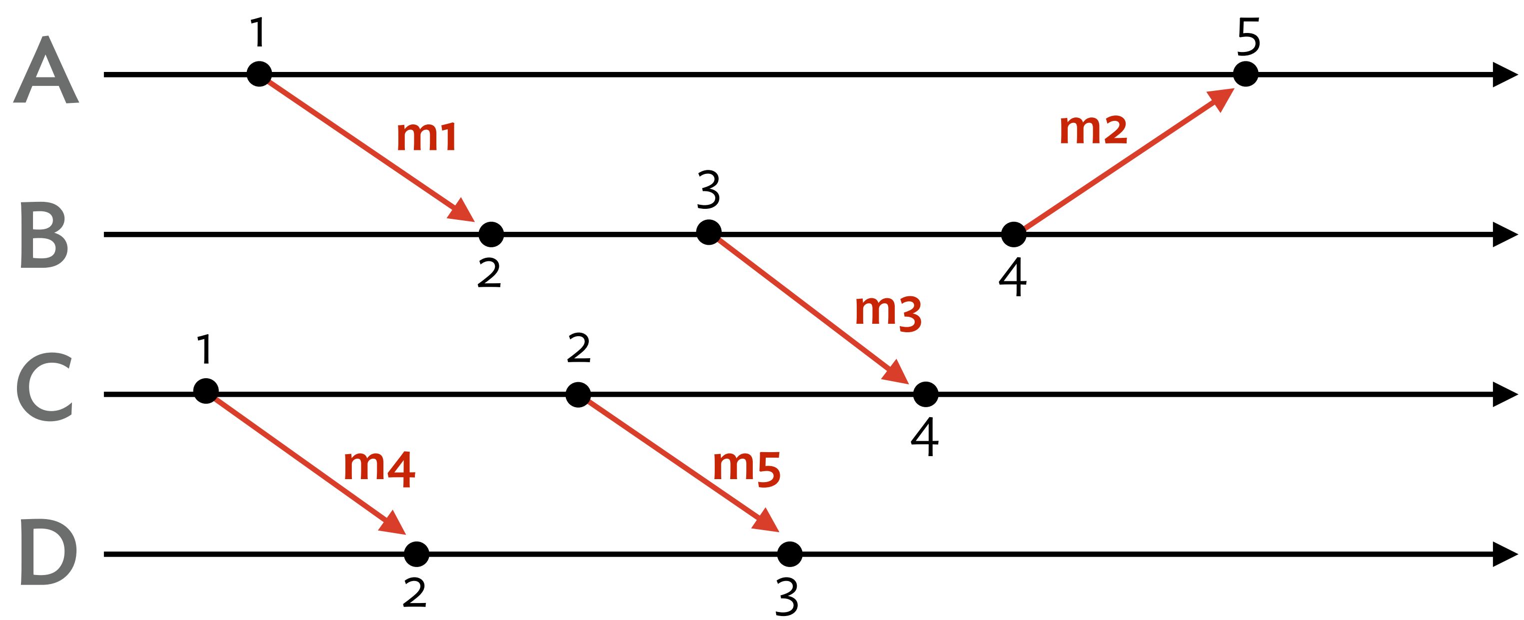
- If *e1* || *e2*, it does not imply causality
  - *Potential* causality is implied
  - E.g., process may receive message before unrelated event

- But, still pretty useful
  - How to implement logical ordering in a real system?

Logical clocks

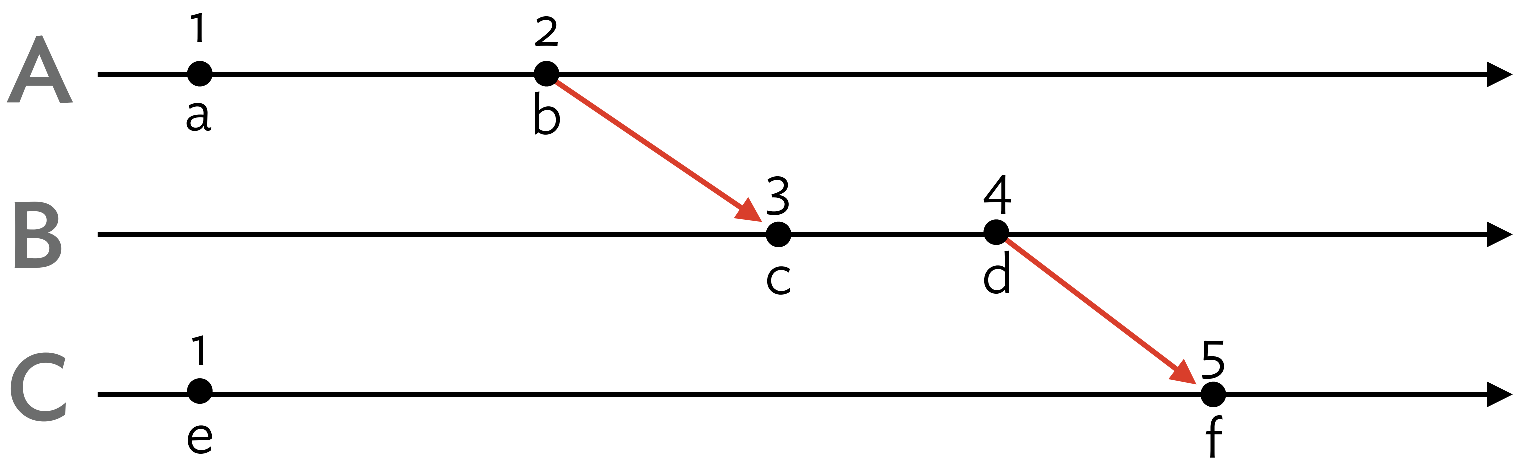
- Lamport created way to create logical clock from ordering
- Define *logical clock* to be a monotonically increasing value
  - Numeric abstraction
  - Meaningless value by itself
- Each host *i* maintains internal logical clock L_i
  - L_i is incremented after each event
  - L_i is piggy-backed on each message sent
  - Upon receipt of message with *t*
    - Set value to $max(L_i, t) + 1$

Example of logical clocks



- For each event *e*, timestamp is longest chain of events that happened-before *e*
- Certain events cause "skipping" of clock
  - *A*'s clock skips from 1 to 5

No reverse implication



- We can observe that $e1 \rightarrow e2 \Rightarrow L(e1) < L(e2)$
  - If *e1* happened before *e2*, then logical clocks ordered
- But the reverse is not true
  - $L(e1) < L(e2) \not\Rightarrow e1 \rightarrow e2$
- In example, $L(e) < L(b)$, but $e \nrightarrow b$
  - In fact, *e* concurrent with all but *f*

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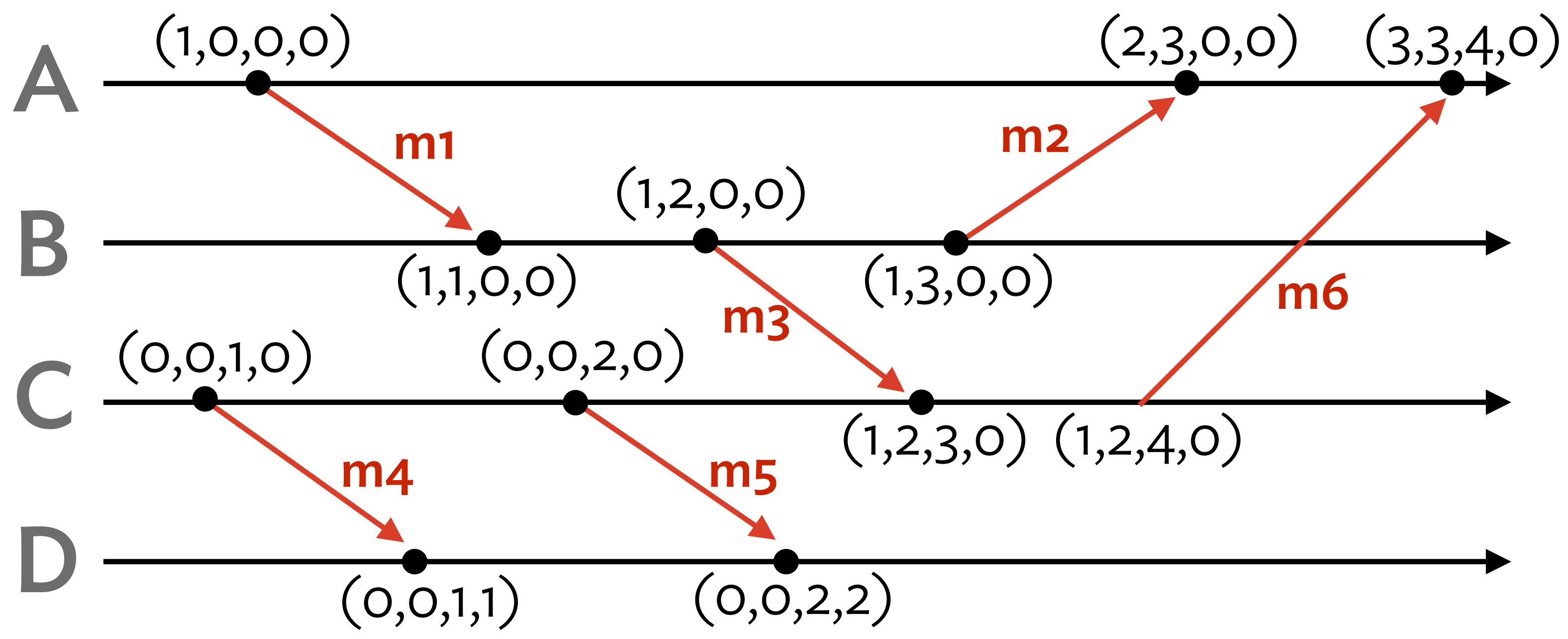
Vector clocks

- Developed to overcome lack of reverse implication
  - Want $L(e1) < L(e2) \Rightarrow e1 \rightarrow e2$
- Processes keep local *vector clock* V_i
  - Array of logical clocks of length N (# processes)
  - Initially [0,0, … 0]
- Similar update procedure to logical clocks
  - $V_i[i]$ is incremented after each event
  - V_i is piggy-backed on each message sent
  - Upon receipt of message with vector clock V_k
    - $V_i[x] = max(V_i[x], V_k[x]) + 1$, for all x

Example of vector clocks



- **Invariant:**

  $V_i[j]$ is the number of events in process P_j that *happened before* the current state of process P_i

Comparing vector timestamps

- Given two vector timestamps V_i and V_j
  - $V_i = V_j$ iff $V_i[x] = V_j[x]$ for all x
  - $V_i < V_j$ iff $V_i[x] < V_j[x]$ for all x
- For example, (2,4,1) < (3,5,9)
- But, other pairs incomparable
  - E.g., (2,4,1) and (3,1,7)
- As with logical clocks $e1 \rightarrow e2 \Rightarrow L(e1) < L(e2)$
  - And also $L(e1) < L(e2) \Rightarrow e1 \rightarrow e2$

Vector vs. logical clocks

- Vector clocks augment logical clocks
  - Use generalization of same mechanism
- Cost: Larger messages, more complexity
  - Often don't know total number of processes
- But, with both can say when certain events happened before each other
- Also, can extent vector clocks to *matrix clocks*
  - Your logical clock + others'